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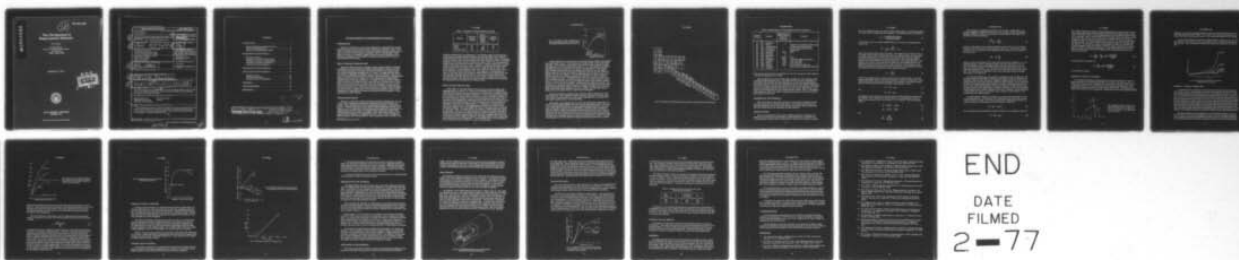
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NRL Report 8064

New Developments in Magnetostriuctive Materials

R. W. TIMME

Standards Branch
Underwater Sound Reference Division
P.O. Box 8337
Orlando, Florida 32806

September 15, 1976



NAVAL RESEARCH LABORATORY
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NEW DEVELOPMENTS IN MAGNETOSTRICTIVE MATERIALS

INTRODUCTION

This report discusses some of the recent developments in magnetostrictive materials—specifically the rare earth-iron alloys and their application to Navy sonar. After a brief review of transduction materials used in sonar, their preferred material properties, and the history of the rare earth-iron alloys, the discussions will be on the properties of these alloys as a function of composition, magnetic field, and stress; the preparation of the materials; the application of the materials to prototype transducers; and the future of these materials in sonar systems.

Review of Transduction Materials in Sonar

Before the 1950's the choices of energy-conversion materials available to designers of underwater sound transducers were limited to magnetostrictive metals such as nickel and its alloys and natural or man-grown piezoelectric crystals such as quartz, rochelle salt, ammonium-dihydrogen-phosphate, and a few others. The magnetostrictive metals were superior in ruggedness and reliability but were limited in efficiency. With the discovery in the 1950's of the piezoelectric qualities of the barium-titanate and lead-zirconate-titanate polarized ferroelectric ceramics, use of the magnetostrictive metals declined—primarily because of this lack of efficiency. An example of why the ceramics replaced nickel is found in the AN/SQS-23 system, where 1500 watts of electrical power were required for the nickel transducer to produce 200 watts of acoustic power but only 300 watts of electrical power were required for the ceramic transducer to produce the same 200 watts of acoustic power. From about 1960 the use of ceramics in Navy transducers has been dominant to a degree that it is now used almost exclusively. However recent developments in magnetostrictive materials have prompted further investigation of their applications as acoustic elements.

Preferred Material Properties

Efficiency, power output, receiving sensitivity, frequency bandwidth, size, cost, and a dozen other considerations determine for a transducer engineer the usefulness of a material. Which considerations are most important generally depend on the specific application. Tradeoffs often must be made. Most of these considerations however can be related to one or a combination of several material characteristics such as piezoelectric or magnetostrictive constants, dielectric or magnetostrictive permeability, elastic moduli, coupling coefficient, strain levels, and resistivity. These characteristics depend on bias field, bias stress, temperature, and hydrostatic pressure. Thus, a simple comparison of different materials often becomes difficult. Such a comparison is shown in Table 1 and

Table 1—Comparison of Several Transducer Materials

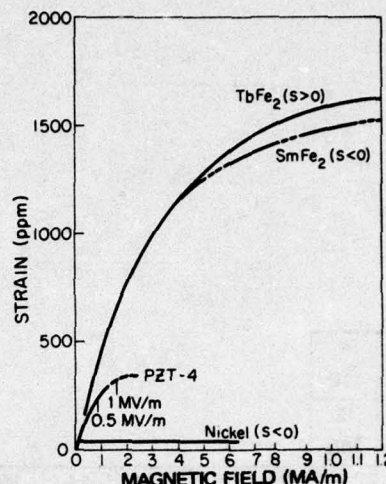
Material	Maximum Coupling Constant	Electro- mechanical Energy Density (J/m ³)	Typical Efficiency (%)
Nickel	0.3	27	15
PZT-4	0.7	630	70
Tb _{0.3} Dy _{0.7} Fe ₂	0.6	6800	?

should be considered only as an introduction. The coupling constant, electromechanical energy density, and typical operating efficiency are shown for nickel, for a commonly used piezoelectric ceramic, and for a recently discovered rare-earth-iron alloy. The coupling constant (a measure of the potential efficiency for energy conversion) of PZT-4 and terbium dysprosium iron is nearly the same and about twice that of nickel. The electromechanical energy density (which relates the amount of electrical or magnetic energy that can be transformed to elastic energy under the proper conditions) is much larger for terbium dysprosium iron than that for the ceramic, which in turn is larger than that for nickel. The typical efficiency of a sonar transducer using nickel or PZT-4 is also shown but cannot as yet be compared to terbium dysprosium iron. The implication of the information in Table 1 is that since the ceramic has greater coupling, efficiency, and energy density than does nickel (and has largely replaced nickel as a transduction material), then the rare earth-iron alloy might have great promise, because it equals or exceeds certain characteristics of the ceramic. This has been the reasoning behind the justification of the research and development effort involving the rare earth-iron alloys.

History of the Rare Earth-Iron Alloys

In the 1960's the rare earth elements were discovered to possess extremely large magnetostrictions—as much as 1%. This was not immediately useful for applications to underwater transducers, because these magnetostrains occurred only at cryogenic temperatures. Research continued, and Clark and Belson [1] of the Naval Surface Weapons Center (then known as the Naval Ordnance Laboratory) and Koon, Schindler, and Carter [2] of the Naval Research Laboratory in 1971 discovered independently and almost simultaneously that the magnetostrains exhibited by binary alloys of certain rare earth elements and iron at room temperatures are 10 to 100 times that of nickel. The possibilities of application to sonar were immediately obvious. A comparison of the strain produced versus field is shown in Fig. 1. The magnetostrains of terbium iron (positive) and samarium iron (negative) are 40 times greater than that of nickel and are not yet saturated at 1.2 MA/m (15 kOe). The strain of PZT-4 as a function of electric field is also shown for comparison. There is no firm relation between the units of the electric field and the magnetic field on the abscissa, except that from an engineering viewpoint, the problems encountered in handling an electric field of 500 kV/m and a magnetic field of 80 kA/m (1 kOe) are about even in degrees of difficulty. The dashed portions of the ceramic strain curve indicate the onset of depolarization. Thus the greater strain of the rare earth-iron alloys as compared to that of ceramic or nickel can be clearly seen.

Fig. 1—A comparison of strain versus field for two rare earth-iron alloys, nickel, and PZT-4 ceramic. (The TbFe_2 and SmFe_2 data come from Ref. 3.)



A slight digression may be appropriate to answer the question, "What are rare earths?" First, they are not "earths." They are a group of transition metals known as the lanthanide series. These are shown in the periodic chart of Fig. 2 as the 15 elements starting with lanthanum, No. 57, and ending with lutetium, No. 71. Each element in the lanthanide series has one more 4f electron than does the preceding element. They all have similar chemical characteristics; some are magnetic, others are not; some are magnetostrictive, others are not; some have magnetic anisotropy, others do not; but, if they are magnetic, they are very magnetic; if they are magnetostrictive, the effect is huge; and if they are anisotropic, the energies are tremendous. This series is a land of the giants. Second, they are not "rare." Gschneidner (Iowa State) [4] has pointed out that there are no availability problems with the rare earths, since many common elements (mercury, cadmium, iodine, selenium, etc.) are less abundant and several more (tungsten, molybdenum, tin, lead, etc.) are just as abundant. Unfortunately rare earths are not cheap. The average cost of a 99.9% pure rare earth is about the same per kilogram as that of research-grade lead-zirconate-titanate ceramic, which is much higher than that of the commercial grade ceramics from which transducers are made. However, if a large market were to develop for the rare earths, their cost could decrease substantially.

Not all rare earths form magnetostrictive alloys that might be applicable to underwater transducers. Table 2 shows the number of useful compounds to be rather small. For a variety of reasons, terbium iron with positive magnetostriction and samarium iron with negative magnetostriction are most promising.

Clark, Belson, and Tamagawa [5] have shown that although these binary alloys exhibit an extremely large magnetostriction, they require large magnetic fields on the order of 1.6 MA/m (20,000 Oe) because of a large magnetocrystalline anisotropy. The feasibility of efficiently generating such a large field in a transducing device is assailed by practical problems. Further investigations by Williams and Koon [6] and by Clark [3] have shown that the anisotropy of a ternary alloy of terbium holmium iron or terbium dysprosium iron can be much lower than that of the binary alloy; and although the magnetostrain may be somewhat reduced, it may still be 20 times that of nickel. A number of investigators [7-9] have measured the magnetomechanical properties of the terbium

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3 Li	4 Be						
11 Na	12 Mg						
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	
55 Cs	56 Ba	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm
87 Fr	88 Ra						

63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
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Lanthanide Series

Rare Earth Elements

Fig. 2—The position of the lanthanide series—the rare earths—in the periodic chart of the elements

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Table 2—Magnetostriction of Rare Earth-Iron (RE-Fe₂) Compounds

Atomic Number	Element	Magnetostrain of RE-Fe ₂ Possible at Room Temperature	Remarks
57	La — lanthanum	0	—
58	Ce — cerium	—	Easily forms nonmagnetostrictive state
59	Pr — praseodymium	—	Forms wrong crystal structure
60	Nd — neodymium	—	Forms wrong crystal structure
61	Pm — promethium	—	Radioactive
62	Sm — samarium	-2100	O.K.
63	Eu — europium	0	—
64	Gd — gadolinium	0	—
65	Tb — terbium	+2460	O.K.
66	Dy — dysprosium	+1260	Very large magnetic anisotropy
67	Ho — holmium	+185	O.K., but small
68	Er — erbium	-300	O.K., but small
69	Tm — thulium	-4250	Low Curie point; high cost
70	Yb — ytterbium	—	Easily forms nonmagnetostrictive state
71	Lu — lutetium	0	—

holmium iron system, and other investigators [10-12] have measured the same properties of the terbium dysprosium iron system.

Koon and Williams [13] have recently begun investigations of the quaternary alloys of terbium holmium dysprosium iron. They find that for a rare earth composition of 20% terbium, 58% holmium, and 22% dysprosium the lowest order magnetocrystalline anisotropy constants are near zero and comparable to that of nickel, while the magnetostriction is still very large. This alloy may turn out to be the best yet, although it is expected to retain an appreciable internal strain energy which may require magnetic fields on the order of tens of kiloamperes per meter (several hundred oersteds). Even so, this magnetic-field requirement is about two orders of magnitude improvement over that for the first binary alloys of terbium iron.

PROPERTIES OF THE MATERIALS

Only the properties of the terbium holmium iron and terbium dysprosium iron ternary alloy systems will be discussed in this section. The ternaries are more useful for transducer application than are the binaries because of the lower magnetic-field requirement and because data on the quaternaries are still preliminary.

Properties of Interest

How does one decide the relative merits of different materials for application to transducers? Probably the most universally accepted characteristic of a material is its electromechanical coupling constant, because this is a measure of the degree of coupling

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that can be obtained between the electrical and mechanical sides of a transducing material. It is a basic index of energy-conversion capability. The coupling constant k is defined as

$$k^2 = \frac{\text{converted stored energy}}{\text{stored input energy}}. \quad (1)$$

It can be shown [14] in a rather simplified manner for the case of a magnetostrictive material that

$$k^2 = \frac{ES^2}{ES^2 + |\kappa| + \epsilon + \delta}, \quad (2)$$

where E is Young's modulus and S is the strain. The numerator is the portion of the input energy which has been converted and stored as mechanical energy. The denominator is the input energy which is stored in the form of the mechanical work, the magneto-crystalline anisotropy energy κ , the internal strain energy ϵ , and the demagnetization energy δ due to end effects and internal inhomogeneties. The coupling will have a value between zero and unity. Since the last three terms in the denominator represent loss mechanisms from the viewpoint of useful energy conversion, one can easily see the desirability of striving for low anisotropy, small internal strains, and homogeneous samples. The coupling can also be related to more basic material properties:

$$k^2 = \frac{d^2}{\mu^T \Delta H}, \quad (3)$$

where d is the magnetostrictive constant relating strain to magnetic field, μ^T is the free magnetic permeability, and ΔH is the elastic compliance modulus at constant field. These material properties are defined more completely in the derivation of the thermodynamic equations of state shown below for describing a magnetostrictive material:

$$S = \Delta^H T + dH \quad (4)$$

and

$$B = dT + \mu^T H. \quad (5)$$

The symbols in these equations are consistent with the "IEEE Standard on Magnetostrictive Materials" [15]. Equations (4) and (5) describe tensor relationships; but in the special case reported here, only the 3-3 mode is to be considered. Thus the equations become

$$S_3 = \Delta_{33}^H T_3 + d_{33} H_3, \quad (6)$$

$$B_3 = d_{33} T_3 + \mu_{33}^T H_3, \quad (7)$$

and

$$k_{33}^2 = \frac{d_{33}^2}{\mu_{33}^T \Delta_{33}^H}. \quad (8)$$

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The coupling can be determined by either of two methods: measurement of the motional impedance or independent measurements of d_{33} , μ_{33}^T , and Δ_{33}^H . The motional impedance method is described in the Summary Technical Report of the NDRC [16] and yields an effective coupling k_e :

$$\frac{k_e^2}{1 - k_e^2} = \frac{D_z}{X_c Q_z}, \quad (9)$$

where D_z is the diameter of the motional impedance circle in ohms, X_c is the clamped reactance at resonance, and Q_z is the mechanical quality factor. The effective coupling is related to k_{33} in the absence of flux leakage and for the special case of a toroid or a very long rod by

$$k_{33}^2 = k_e^2 \frac{\chi_R}{\chi_0^2}, \quad (10)$$

where χ_R is the real component of the eddy-current factor whose magnitude is χ_0 . The motional impedance method is probably simplest if the eddy-current loss is very low. This would require a long, slender sample which would have a low frequency of resonance, or a laminated sample. For a short sample with large eddy-current losses, the independent measurement of d_{33} , μ_{33}^T , and Δ_{33}^H at low frequencies would be most satisfactory. This method has been described in Ref. 9, and with proper care both methods yield results in close agreement.

The material properties d_{33} , μ_{33}^T , and Δ_{33}^H are important in their own right also. The incremental magnetic permeability is important to the designer because it determines the reluctance of the flux path, the amount of magnetic fringing, and the size of the current-carrying solenoids, and for these aspects should be as large as possible. On the other hand the desire for a large coupling, large hydrophone constant, and low eddy-current loss requires a small incremental permeability. The elastic compliance modulus Δ_{33}^H determines the speed of sound in the material and the frequency of resonance as well as the coupling. A large modulus means a smaller transducer can be built to resonate at a given frequency. A large modulus also means a low specific acoustic impedance, which results in a low mechanical Q and a large bandwidth.

In magnetostrictive materials the constant d_{33} is important for hydrophone as well as projector applications. The sensitivity M of a hydrophone that uses a sense coil with n turns to detect the change in flux density produced by a magnetostrictive element of cross-sectional area A in the presence of a sound pressure P is given by

$$M \equiv \frac{V}{P} = d_{33} \omega n A. \quad (11)$$

For a hydrophone using a piezoelectric element of thickness t , the sensitivity is given by

$$M \equiv \frac{V}{P} = g_{33} t. \quad (12)$$

Each of these equations is derived with the assumption that the sound is incident only on the element surfaces whose normal is parallel to the direction of magnetization or polarization. When this is not the case, the magnetostrictive and piezoelectric constants become more complicated because other elements of their respective tensors are included. As can be seen from Eqs. (11) and (12), the sensitivity of a magnetostrictive or piezoelectric hydrophone depends on physical dimensions and, in the one case, frequency and number of sense coil turns. These factors make a direct comparison of the two dissimilar materials difficult. The hydrophone constant, as discussed by Woollett [17], combines the electrical impedance Z with the sensitivity to provide a better comparison of the relative merit of materials for hydrophone application. In the following two equations this expression is shown reduced in both the magnetostrictive and piezoelectric cases to the same functional form:

$$H \equiv \frac{M}{\sqrt{|Z|}} = \frac{d_{33}}{\sqrt{\mu}} \sqrt{\omega A t} \frac{\text{volts/pascal}}{\sqrt{\text{ohms}}} \quad (13)$$

for magnetostrictive materials and

$$H \equiv \frac{d_{33}}{\sqrt{\epsilon}} \sqrt{\omega A t} \frac{\text{volts/pascal}}{\sqrt{\text{ohms}}} \quad (14)$$

for piezoelectric materials.

Properties as a Function of Composition

The material characteristics change greatly with rare earth composition in both the terbium holmium iron and terbium dysprosium iron ternaries. The variation in the coupling constant with rare earth composition for the two ternary systems is shown in Fig. 3. A maximum coupling of 0.6 was found [10] for 26% terbium-74% dysprosium, which surpassed the 0.45 maximum found for 23% terbium-77% holmium. The maxima are the result of the interaction of two mechanisms—magnetostrictive activity and magnetocrystalline

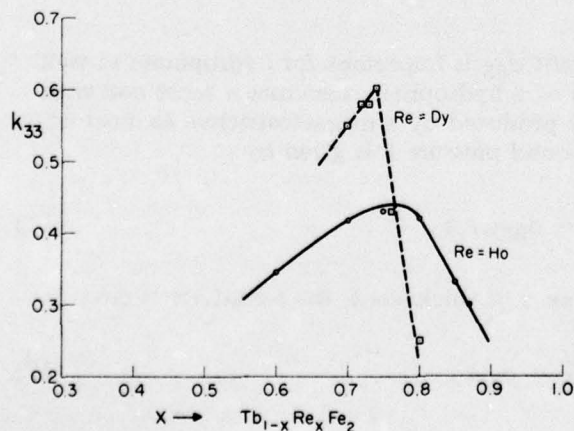


Fig. 3—Magnetomechanical coupling of the terbium dysprosium iron and terbium holmium iron ternary systems as a function of rare earth composition. (The TbDyFe data come from Ref. 10.)

anisotropy. In each case the magnetostriction to the left of the peaks increases but the anisotropy magnitude increases faster. To the right of the peaks the magnetostriction decreases while the anisotropy again increases—thus the more rapid decline in the coupling.

In the terbium holmium iron system the magnetostrictive constant d_{33} and the modulus ΔH_{33} have a similar variation with composition but reach a maximum at 20% terbium-80% holmium. The incremental permeability μ_{33}^T changes with composition as shown in Fig. 4.

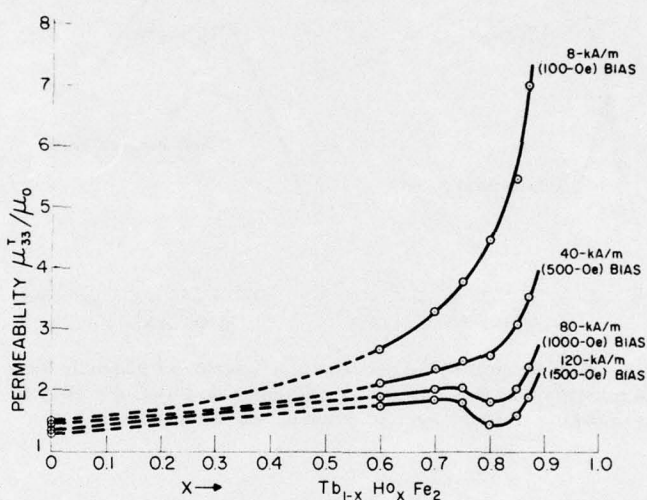


Fig. 4—The incremental permeability as a function of composition for $Tb_{1-x}Ho_xFe_2$

Properties as a Function of Magnetic Bias

A comparison of the coupling for two alloys near the optimum rare earth composition is shown in Fig. 5. The properties are functions of the magnetic bias field which must be externally applied because the alloys have only a small magnetic remanence. At a bias field of 19 kA/m (240 Oe) the 30% terbium-70% dysprosium iron alloy has a maximum in k_{33} of 0.60, which is to be compared with 0.43 for 25% terbium-75% holmium iron and 0.27 for oxide annealed nickel. These curves show the rare earth-iron alloys have a greater potential capability for energy conversion over a wider range of bias field than does nickel. The broad peak in the coupling implies that the alloys would retain their high values of coupling under high-power drive conditions. The coupling versus bias flux density is also shown in Fig. 5, because in many applications the flux density within the material is easier to measure. The coupling peaks at about 0.67 tesla (6700 G) for the terbium dysprosium iron, 0.46 T (4600 G) for the terbium holmium iron, and 0.38 T (3800 G) for the oxide annealed nickel.

The apparent difference in the shapes of the coupling-versus-flux-density curves for the two alloys is due to the striking difference found in their static magnetic permeabilities. The static and incremental permeabilities are shown in Fig. 6. The static permeability of the terbium dysprosium iron reaches a maximum of 150 at 1.2 kA/m (15 Oe) and is still

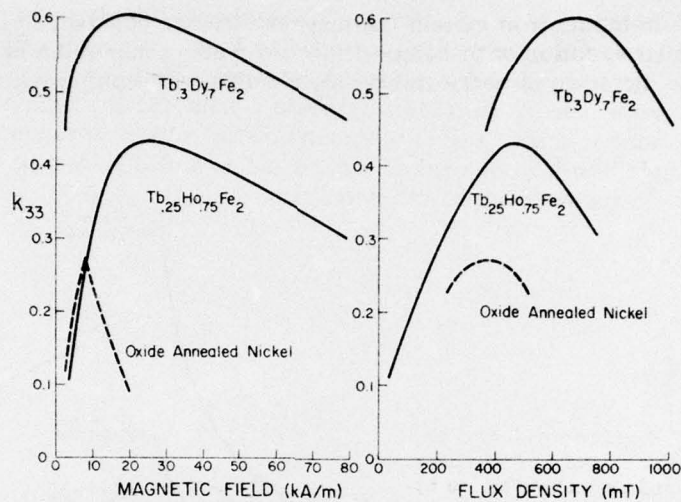


Fig. 5—Magnetomechanical coupling as a function of magnetic bias-field intensity and flux density for a TbDyFe and TbHoFe alloy of near optimum composition and oxide annealed nickel

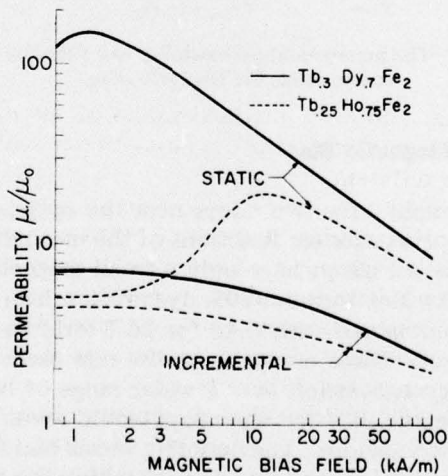
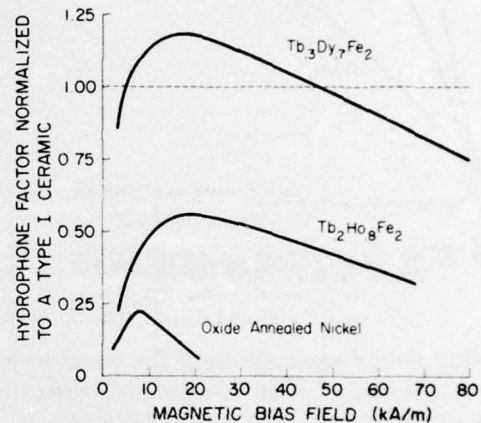


Fig. 6—Magnetic permeability as a function of magnetic bias field for two rare earth-iron compositions

as high as 38 at 12 kA/m (150 Oe), at which the terbium holmium iron maximizes at 19. The incremental permeabilities are more similar in general shape, but the values for the terbium dysprosium iron are again larger.

A comparison of the hydrophone factors for 30% terbium-70% dysprosium iron, 20% terbium-80% holmium iron, and oxide annealed nickel to that of a piezoelectric ceramic is presented in Fig. 7. Typical values for a Navy type I ceramic ($d_{33} = 2.8 \times 10^{-10}$ m/V, $\epsilon = 1.15 \times 10^{-8}$ F/m) were used in Eq. (14) to provide a value for the normalization of Eq. (13). The hydrophone factor of the terbium dysprosium iron is considerably larger than for the terbium holmium iron or oxide annealed nickel and is shown to be comparable to the ceramic over a wide range of magnetic bias.

Fig. 7—The hydrophone factor of oxide annealed nickel and two rare earth-iron alloys as a function of magnetic bias field and normalized to the hydrophone constant of a type I (PZT-4) ceramic



So far this report has dealt with only low-field values of the material characteristics; but if the material is used in a sound projector operating under a high-power drive, these characteristics certainly will be different.

The room-temperature magnetostrains of the 30% terbium-70% dysprosium iron and 30% terbium-70% holmium iron alloys and oxide annealed nickel are compared in Fig. 8. The greater anisotropy of the rare earth-iron alloys is readily apparent from the more gradual increase of strain toward saturation; however the much larger strains possible with the rare earth-iron alloys are self-evident. The oxide annealed nickel saturates quickly to a negative strain of 36 ppm, whereas the 30% terbium-70% holmium iron exhibits a positive strain of 480 ppm and the 30% terbium-70% dysprosium iron reaches a positive strain of 750 ppm at 150 kA/m, (1900 Oe) and both are still far from saturation. The strain exhibited by a type I ceramic (PZT-4) is again shown for comparison with the same reservations as before.

In an application as a projector the alloy will be placed in a bias field, since the magnetic remanence is too small, and the dynamic strain will be produced by an applied alternating magnetic field. For a constant bias field of 40 kA/m (500 Oe) and a superimposed alternating field, the magnitude of the dynamic strain of the 30% terbium-70% dysprosium iron alloy produced at the same frequency has been found to increase with

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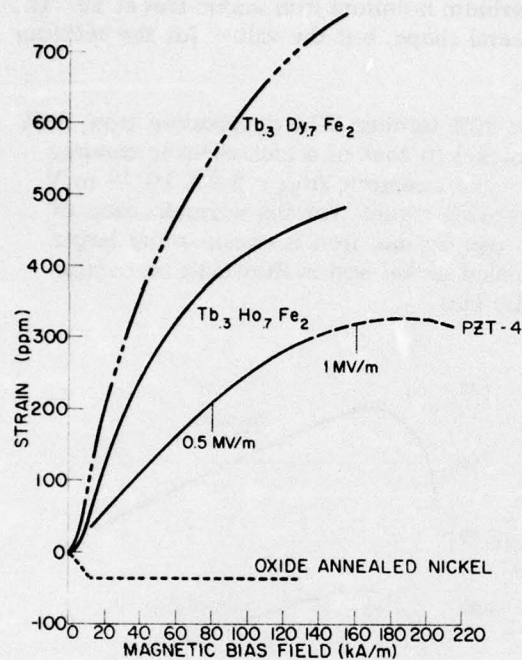


Fig. 8—Strain of two rare earth-iron alloys and oxide annealed nickel as a function of magnetic bias field and of a type I (PZT-4) ceramic as a function of electric bias field

alternating field magnitude until the mean-to-peak magnitude approaches about 32 kA/m (400 Oe). At this point some frequency distortion of the dynamic strain begins to occur. The 450-ppm peak-to-peak strain thus obtained will produce significantly more sound than the 36-ppm maximum of nickel because the sound pressure level generated is directly proportional to the displacement.

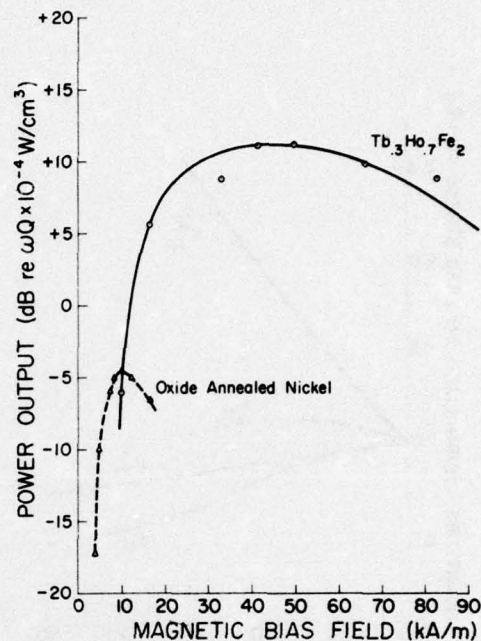
From these high-drive measurements of the rms magnetostrain and the following equation, an estimate can be made of the maximum power output of which the material is capable:

$$P = \frac{\omega S^2 Q \times 10^{-7}}{\Delta B_{33}} \quad (15)$$

An example of this power capability is shown in Fig. 9 for a 30% terbium-70% holmium iron alloy. The maximum undistorted strain at 159 Hz (to avoid eddy-current losses) for a given bias field was used to obtain the power at that bias. Since the mechanical Q (which involves the engineering application and not the material itself) and the frequency (which is variable) are involved, the power output has been expressed in decibels referenced to $\omega Q \times 10^{-4}$ W/cm³. This rare earth composition of 30% terbium-70% holmium iron should be capable of generating at least 16 dB more power than does nickel and the same amount of power as does a type I piezoelectric ceramic (PZT-4) under a 500-kV/m rms drive. Based on the greater magnetostrain of the terbium dysprosium iron as shown in Fig. 8 and also on its lower stiffness moduli, a power output curve about 4.5 dB larger can be expected for 30% terbium-70% dysprosium iron than that shown in this figure for the 30% terbium-70% holmium iron.

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Fig. 9—Maximum undistorted power output for a TbHoFe alloy and nickel



Properties as a Function of Stress Bias

Normally acoustic elements in an underwater sound projector are biased with a mechanical compressive stress. This is to prevent the element from undergoing tensile failure at high drive levels, to shock harden the element, and to dampen spurious resonances. Thus it is likely these alloys will also be bias stressed in any operational design. For this reason the effects of one-dimensional compressive stress parallel to the direction of magnetic polarization have been investigated.

The results of the study on Tb_{0.3}Dy_{0.7}Fe₂ are shown in Fig. 10. A constant magnetic bias was maintained while the sample was stressed. The results shown are for a 16-kA/m (200-Oe) bias, but the changes appeared to be independent of magnetic bias. The magnetostrictive constant d_{33} and the permeability μ_{33}^T decreased while the elastic constant $1/\Delta \frac{B}{33}$ and the sound speed increased. The cumulative effect is that the coupling increases gradually to 113% at 17 MPa (2500 p.s.i.) and then begins a slow decline.

Figure 11 shows the strain produced upon stressing the 30% terbium-70% dysprosium iron to failure. Catastrophic failure occurred without prior warning for two samples tested at almost the identical stress of 500 MPa (73,000 p.s.i.). This is about the same compressive failure point as for type I ceramic.

Conclusions About the Properties

The preceding comparison of the magnetostrictive properties of the ternary alloys of terbium holmium iron and terbium dysprosium iron as a function of composition, low- and high-power drives, and the effects of stress bias yields the following conclusions:

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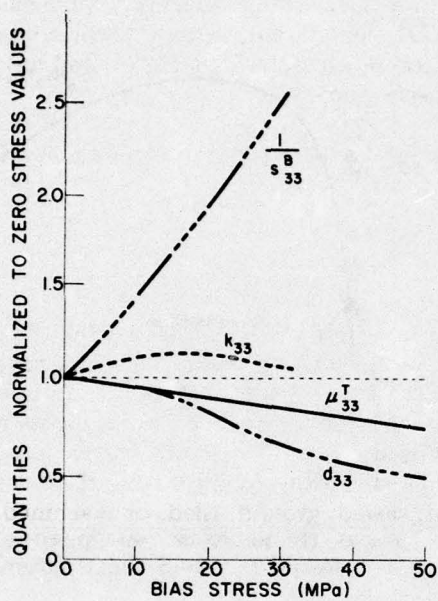


Fig. 10—Effects of bias stress on $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$ at a constant magnetic bias field of 16 kA/m (200 Oe)

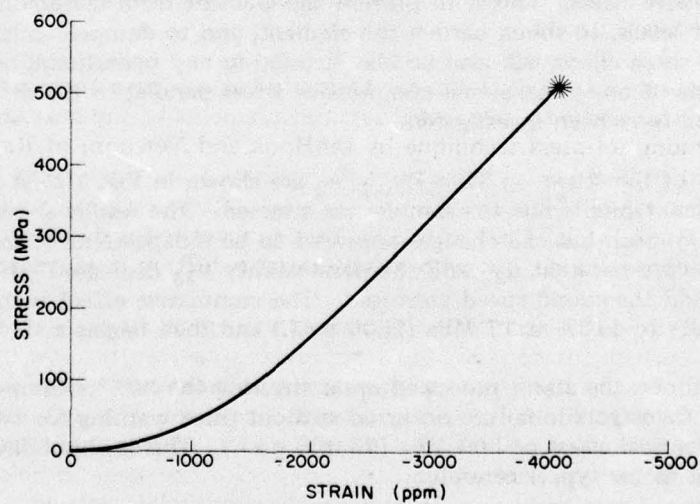


Fig. 11—Stress-strain to failure for $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$

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- The terbium dysprosium iron alloy with a rare earth composition of approximately 30% terbium-70% dysprosium has been found to have a magnetomechanical coupling, hydrophone factor, maximum power output, magnetic permeability, and magnetostrain surpassing the best of the terbium holmium iron system. The terbium holmium iron alloys were not annealed as were the terbium dysprosium iron alloys, and an annealing process will possibly improve their performance somewhat.
- The terbium dysprosium iron alloy with about 30% terbium can compare favorably with piezoelectric ceramics as a projector material.

PREPARATION OF THE MATERIALS

The magnetostrictive rare earth-iron alloys have not yet been prepared in large quantities. The largest samples have been made by Gschneidner of Iowa State and have been about 12 cm long by 1.5 cm in diameter and have been polycrystalline. They were made by arc melting the proper proportions of the starting materials and casting ingots in an argon atmosphere. Annealing the cast ingot will improve the magnetostrictive properties—especially for the terbium dysprosium iron alloys—probably by improving the homogeneity of the material. The ternaries can be spark cut, sawed, ground, filed, or machined on a lathe to the required shape. The point of contact with the machine tool must be bathed in cutting oil to keep the shavings from burning.

When preparing these materials, one should keep in mind the high chemical reactivity of the rare earth elements. Because of this chemical reactivity, which is even more pronounced at high temperatures, and the tendency toward brittleness at lower temperatures, the usual mass-production methods of rolling or drawing may be complicated. More work is needed in this area.

Single crystals 1 to 2 cm long and 1 cm in diameter have been grown by Milstein and Koon of NRL and have been used for measurements of the anisotropy and magnetostrain. A vacuum hot-press technique by vanHook and Newborn of Raytheon has successfully produced disks 2 cm in diameter by 1 cm thick. A plasma spray technique by Taylor of Union Carbide has produced toroids of terbium dysprosium iron about 6 cm in diameter and 1 cm thick. Clark of NSWC has encapsulated terbium dysprosium iron powder in an epoxy matrix but with a substantial reduction in magnetostrictive properties.

The magnetic and magnetostrictive properties depend strongly on the methods of fabrication. Grain orientation will yield improved properties because of increased magnetostrain and decreased internal strains at grain boundaries. A large porosity will decrease the coupling and inhibit rapid domain-wall motion. The abilities to produce large sizes of various configurations and to laminate, all at low cost, are important criteria. The techniques mentioned are preliminary; although some seem to hold more promise than others, more work is needed to develop the production methods.

APPLICATION OF THE MATERIALS

Even before the properties of the rare earth-iron compounds were completely known, plans were being made to incorporate the new material into experimental transducer

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designs. The first designs have been restricted to low-power and low-frequency operation because the rare earth-iron alloys have been available in only small quantities in the form of short, nonlaminated, arc cast rods. Terbium dysprosium iron alloys have been used exclusively in the experimental transducers because of their large coupling and magnetostrain.

Design Description

The transducer development conducted by the Underwater Sound Reference Division (USRD) of the Naval Research Laboratory has had the objective of a piston-type k_{33} -mode sound projector for nonresonant, broadband frequency operation. The design was to allow intercomparison of the terbium dysprosium iron and ceramic elements as well as comparison with predictions based on basic material properties measurements. It was fully expected that the operational characteristics of the transducer might be less than optimum because the design was initiated before the alloys were completely investigated.

An illustration of the USRD experimental transducer is shown in Fig. 12. The overall size and shape are similar to an existing ceramic transducer currently being used—the USRD type G23J. Three rods of 27% terbium-73% dysprosium iron, 1.3 cm in diameter by 5 cm long, are the active elements. They are stress biased to 12 MPa (1700 p.s.i.) between the front piston diaphragm and the back mass. The back mass has been made larger than necessary to ensure all radiation comes from the front piston. The stress bias is maintained by a center bolt which also provides the dc magnetic bias. A solenoid with a turn density of 20 turns per millimeter is formed by winding 24 AWG copper wire about the stress bolt. This is capable of providing a bias flux density of 0.4 T (4000 G) on each of the rare earth-iron rods which are evenly spaced on a 9.25-cm-diameter circle. Each of the terbium dysprosium iron rods is within a solenoid which has a turn density of 21 per millimeter

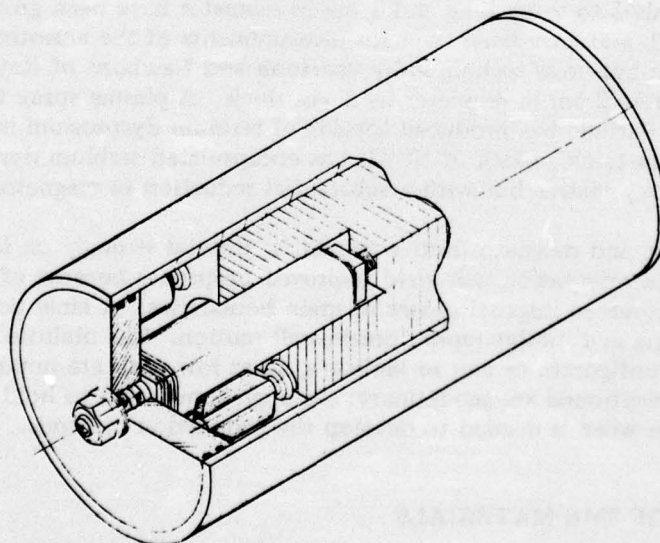


Fig. 12—An experimental piston-type k_{33} -mode underwater sound transducer using $\text{Tb}_{0.23}\text{Dy}_{0.73}\text{Fe}_2$

(24 AWG copper wire). Additional dc bias can be applied by these solenoids as well as the dynamic field. Typical operating conditions for measuring transmitting current response (TCR) are 0.3 A dc through the center solenoid, 1.0 A dc through the rod solenoids, and 0.1 A rms ac through the rod solenoids. This results in a bias flux density of 0.6 T (6000 G) or a field of 14 kA/m (175 Oe) and an rms dynamic flux density of 10 mT (100 G) or an rms field of 1.35 kA/m (17 Oe) on the terbium dysprosium iron rods. The heat generated by the I^2R loss under this condition is 25 watts. Not shown in the figure is a pump and radiator assembly on the outside of the casing that provides forced cooling of the transducer fluid and the rods. Cooling is necessary for continuous-wave operation above 50 watts.

Operating Characteristics

The experimental transducer is being evaluated now. Results are still preliminary and incomplete, and measurements have been made only at low-power drive. However, the operating characteristics obtained so far have been encouraging and are nearly as predicted by the design calculations that were based on the measured material properties.

The TCR of the experimental transducer is shown in Fig. 13. For comparison the TCR of the G23J ceramic transducer is shown as the dashed line. The general shape of the TCR is correct for magnetostrictive transducers—an ω^2 dependence below resonance and an independence of ω above resonance, except for flexural resonances of the front plate. Piezoelectric projectors characteristically have an ω dependence below resonance. The experimental transducer resonates at 2700 Hz with a Q of 5, and the G23J resonates at 12,000 Hz. This difference is partially due to the 50% lower sound speed in the terbium dysprosium iron and partially due to the iron piston of the experimental transducer and the magnesium piston of the G23J. Both the resonance frequency and the magnitude of the TCR at low frequencies are close to the predicted values. Retrospect now shows

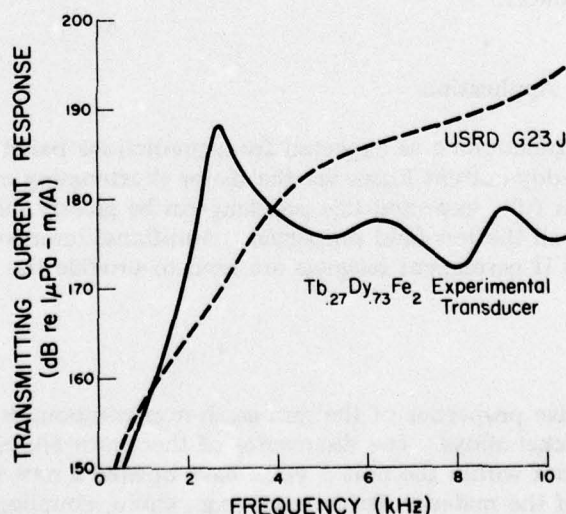


Fig. 13—Transmitting current response of the rare earth-iron magnetostrictive transducer and the USRD G23J piezoelectric ceramic transducer

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the front piston could have been half as thick and still have carried the desired flux density. This reduction in thickness would increase the TCR and the resonance by about 40%. Since nonlaminated rods and soft-iron flux paths were used in the construction, eddy-current losses are extremely pronounced at the higher frequencies. With laminations of the rods and the use of the transformer-grade laminations of silicon steel in the transducer, the TCR above 1 kHz should be increased.

The effect of the eddy current is obvious from the measured values of the transducer's effective coupling coefficient. Values of the effective coupling at two bias flux densities are shown on Table 3. A rather simple-minded correction factor for the eddy-current loss is shown in the third column, and the true material coupling is shown in the fourth column. Some encouragement is gained by noting that the slope of the coupling with flux density is the same for all three columns. This implies improvement will result from the use of laminations.

Table 3—Coupling Coefficient of the $\text{Tb}_{0.27}\text{Dy}_{0.73}\text{Fe}_2$
Experimental Transducer

B_{bias} (mT)	k_e	k_e (simple correction)	k_{33}
300	0.11	0.16	0.35
400	0.23	0.33	0.48

The efficiency of the experimental transducer was calculated from measurements of the impedance loci in air of the transducer when assembled but not oil filled and the loci in water of the transducer when oil filled and found to be 35% (this technique is described in Ref. 16). This efficiency is about twice that of a nickel transducer and about half that of a piezoelectric transducer.

Conclusions About the Application

The transducer is functioning as expected from predictions based on the material characteristics. Large eddy-current losses are the major shortcoming of the present experimental transducer. It is fully expected this problem can be greatly reduced and an improvement obtained in all the low-field properties. Additional improvement, especially in efficiency, can result if permanent magnets are used to provide the magnetic bias.

DISCUSSION

The magnetostrictive properties of the rare earth-iron compounds are vastly superior to the more familiar nickel alloys. The discoveries of these new alloys and the characterization of their properties within the past 5 years have opened a new era in magnetostrictive materials. Many of the material design goals (e.g., strain, coupling, low eddy-current loss, and high-power capability) that were established by the sonar designers and engineers 10 years ago have been met or exceeded. But, as is always the case, a price must be paid.

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For these materials that price not only includes cost but also the need of large magnetic fields and a brittleness similar to ceramic. In addition, some designers may be hesitant to accept magnetostrictive alloys simply because magnetic fields are inherently more difficult to route and control than electric fields. Before becoming discouraged, however, one should remember that these materials have not been known very long and that, at a similar point in development, ceramics were also looked upon with some doubt.

The continuing development program for the rare earth-iron alloys is healthy, with there being an enthusiastic group of investigators and a multitude of avenues open for further improvement. The aforementioned need of large magnetic fields may be greatly reduced by the quaternary alloys, or permanent magnets may be used to provide the bias and thereby partially remove the need for large current-carrying coils. The problem of brittleness in ceramics has partially been solved, and similar techniques could be applied here. Grain orientation is expected to further improve the magnetostrain and coupling.

The rare earth-iron alloys are not yet optimized for transducer application—partially because of limited fabrication techniques for various shapes and sizes. The performance of the experimental transducers has suffered somewhat because their designs were undertaken before the material properties were fully known, but they were successful in demonstrating the potential of these materials and indicating in what areas special care would be necessary.

At this point the outlook for a major fleet-sonar system design using a rare earth-iron alloy is cloudy and premature. For many reasons ceramics are not threatened by competition from these alloys, but a complimentary role is quite possible. At present, application in low-frequency, high-power transducers appears promising.

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